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13. ABSTRACT (Maximum 200 words)  Our objective addresses the mechanics models needed and the suppression techniques offered by smart materials as applied to optical systems mounted on satellites. The objectives of this research effort are to model the dynamics and control of flexible optical systems for both vibration suppression and shape control using smart materials as the actuation component and sensing component. The specific objective was to model a generic system, select suitable actuation, sensing and control elements, develop a system model, and verify the results against a proof-of-concept experiment. The results of this three-year grant can be summarized as follows: <ul style="list-style-type: none"> <li>• Actuator Material Selection</li> <li>• Ground Testing of an Inflated Torus</li> <li>• Finite Element Modeling</li> <li>• Mechanics Modeling</li> <li>• Comparison of Inflated Torus Models and Tests</li> <li>• Control Analysis <ul style="list-style-type: none"> <li>○ Theoretical Designs</li> <li>○ Experimental Implementations and Verifications</li> </ul> </li> </ul> All of the results developed here center around a thin membrane material (Kapton) formed into an inflated torus. A torus forms one of the basic elements of the perceived inflated satellite reflector system. The research results have focused on generic results applied to the specific case of an inflated torus. The inflated torus was chosen because it is a basic element being considered by AFRL.					
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**Final Report**  
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## Smart Structures for Vibration Suppression of Optical Surfaces

(F49620-99-1-0231)

Daniel J. Inman  
G.R. Goodson Professor and Director  
Center for Intelligent Material Systems and Structures  
Department of Mechanical Engineering  
310 Durham Hall, Mail Code 0261  
Virginia Polytechnic Institute and State University  
Blacksburg, VA 24061  
Phone: 540-231-4709 Fax: 540-231-2903  
<http://www.cimss.vt.edu>, email: [dinman@vt.edu](mailto:dinman@vt.edu)

### **Abstract**

Satellite and spacecraft technology is changing rapidly in mission and, hence, in size, configuration and geometry. New satellites with highly precise optical surfaces will vibrate while undergoing rigid motion (repositioning) and as the result of onboard disturbances. These changes require new results in modeling, vibration suppression and ground testing. This effort addresses mechanics models, suppression techniques and ground testing abilities offered by smart materials to provide basic research in support of new satellite designs with optical appendages and made from the new class of inflatable components. Specifically, we focus here on an inflated torus as a basic geometric element of many Air Force satellite systems.

Satellites are becoming smaller, lighter and more flexible, while their performance requirements are becoming more stringent. This is especially true for optical systems and surfaces. Here we examine the support structure for optical surfaces formed from inflated materials and perform research in support of using an inflated torus to retain vibration specifications in view of both rigid body and local disturbances. While we consider both active and passive means, we focused on the use of smart materials to provide the required vibration suppression. Smart materials are most compatible with satellite applications, as they are of low power requirements, unobtrusive and can be fully integrated into a system. Recent construction of inflated torus systems at NASA/AFRL and subsequent ground testing has shown that traditional vibration tests are difficult to perform because of the extreme flexibility of the torus and the rigid body motion of suspended tests coupling with the torus' flexible modes.

The following is a report of our activities over the life of this grant.

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## **2. Summary of Contributions**

Our objective addresses the mechanics models needed and the suppression techniques offered by smart materials as applied to optical systems mounted on satellites. The objectives of this research effort are to model the dynamics and control of flexible optical systems for both vibration suppression and shape control using smart materials as the actuation component and the sensing component. The first year was focused on examining the use of smart materials to control inflated concentrators of an optical system. The specific objective was to model a generic system, select suitable actuation, sensing and control elements, develop a system model, and verify the result against a proof-of-concept experiment. These objectives were met as summarized here.

The results of this three-year grant can be summarized in the following list:

- Actuator Material Selection
- Ground Testing of an Inflated Torus
- Finite Element Modeling
- Mechanics Modeling
- Comparison of Inflated Torus Models and Tests
- Control Analysis
  - Theoretical Designs
  - Experimental Implementations and Verifications

All of the results developed here center around a thin membrane material (Kapton) formed into an inflated torus. A torus forms one of the basic elements of the perceived inflated satellite reflector system. The research results have focused on generic results applied to the specific case of an inflated torus. The inflated torus was chosen because it is a basic satellite component being considered by AFRL.

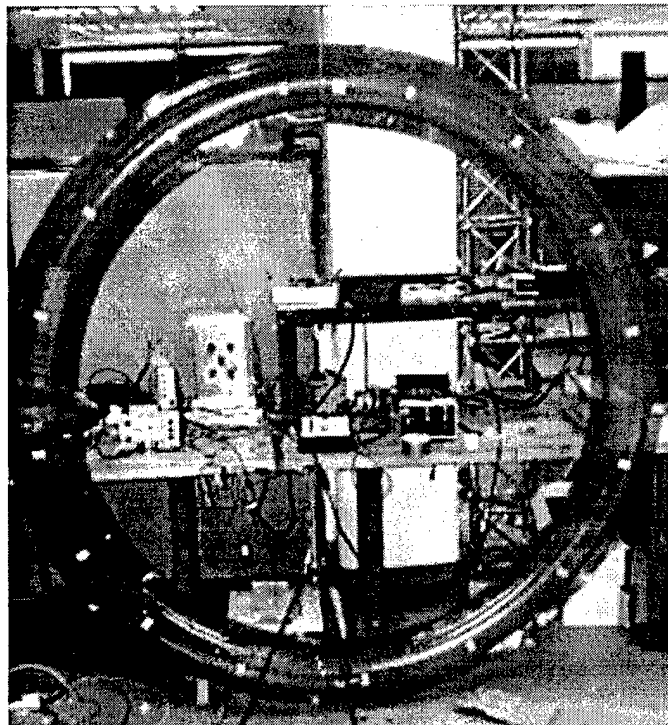
## **Technical Details**

The technical findings of this research program are summarized in this section. The results have been well received in the technical community so that almost all of the results now appear as journal articles (listed), with the most current results given in the recent conference listings. Several additional journal articles are still out for review.

The first year of this project focused on defining a suitable test structure, determining what available actuation and sensing materials could be integrated into an inflated satellite, and use of commercial finite element codes for modeling. Our major accomplishments on support structures are: a) determining that a "membrane" is NOT a suitable model for patch actuation of an inflated torus; b) that we can use PVDF film in a modal test of an inflated torus; and c) that actuation will be required about every  $10^\circ$  around the torus in order to control vibration modes. All three of these findings have significance to AFRL'S efforts to inflatable satellites as these are all problems faced in everyone's attempts to produce an inflated collector. During the first year, a number of

materials besides PVDF films were considered for actuation, and these included: shape memory films, shape memory fabrics and conventional accelerometers. The only useful material for sensing turned out to be the PVDF films, partially because commercial grades were readily available. During the first year, only samples of Kapton were used, and our attempt at testing focused on truck tires and a child's swimming pool as experimental test beds for understanding the dynamics of a torus.

During the second year, we were fortunate to have received a 1.5-m diameter, Kapton torus from John Main of the University of Kentucky (see Figure 1). This was indeed a huge improvement over the truck inner tube we had been using, as the wall thickness, torus and ring diameters are key parameters in determining the nature of the dynamics. We constructed a detailed model of a generic torus system as a baseline for researching the smart materials' applicability to vibration suppression of flexible satellites. In addition, we selected specific smart materials for use in a suppression system and in ground testing. The mechanics modeling to date has focused on dynamic models of an inflated torus with patch piezoceramic-based actuators, PVDF actuators and PVDF sensors. We invented a new PVDF bimorph actuator, obtained a new Macro Fiber Composite<sup>TM</sup> (MFC) actuator from NASA Langley Research Center, and started our modeling of the torus to include these devices.



**Figure 1. The inflated torus test facility with smart sensors and actuators.**

We have successfully ground tested this torus and started the preliminary vibration suppression research. The key finding in the second year was that by using MFC actuators and PVDF sensors, we were able to solve the ground testing problem plaguing all ground tests of large, ultra-flexible inflated structures at both NASA and AFRL.

Vibration ground testing of the AF 10-m torus was not feasible because conventional test hardware (shakers and accelerometers) coupled the flexible modes with the suspension modes of the torus, negating test results. Our approach of using surface-mounted smart materials for both sensing and actuating for vibration testing solved this ground testing problem. Furthermore, because our test article was small (1.5 m instead of 8-10 m), we were able to perform both conventional tests and tests based on smart materials, and show their equivalence in identifying the modal properties of inflated devices.

Year-2 major accomplishments were: a) determining that an MFC patch actuation device can both control and excite an inflated torus; b) the design and implementation of a bimorph PVDF film actuator; c) the comparison of various actuation and sensing schemes using smart materials and structures to traditional vibration actuators and sensors; and d) the successful completion of vibration testing solely using smart materials. All four of these findings have significance to AFRL'S efforts to inflatable satellites, as these are all problems faced in any attempt to produce an inflated collector. In addition, we have solved the ground testing issue identified by NASA in its attempt to test an 8-meter inflated torus.

In the last year of support, the major accomplishments were: a) determining that an MFC patch actuation device can both control and excite an inflated torus, producing a viable modal survey of a very flexible inflated object; b) the successful modeling of an inflated shell, showing the need to include geometric nonlinearities in the pre-stressed model; c) the comparison of various actuation and sensing schemes, using smart materials and structures, to traditional vibration actuators and sensors; d) successful modal analysis testing of the torus using multiple sensors and actuators simultaneously; and e) the successful completion of vibration control testing completely using smart materials. This research has successfully developed a multiple-input, multiple-output modal testing technique for large, inflatable structures that extends current laboratory work into real inflatable satellite applications. By using multiple smart sensors and actuators simultaneously, the accurate dynamic analysis and vibration suppression of a true-scale, super structure has been deemed both reliable as well as effective. All of these findings have significance to AFRL'S efforts to inflatable satellites as these are all problems faced in everyone's attempts to produce an inflated collector.

Of particular interest during the third year was the comparison and understanding of various FEM results and the modal testing results. An extensive analysis was performed (as part of Akhilesh Jha's PhD dissertation) of the various commercial FEM codes and shell models from the mechanics community. This led to the discovery of the importance of modeling the internal pressure as a follower force and the discovery of the correct geometric nonlinearity for coupling the pre-stress due to the pressure with the dynamic equations of motion. This discovery correctly explains the error made in modeling a freely-suspended torus using AVAQUA, I-DEAS and ANSYS.

In addition, a successful active control experiment was completed on the test structure shown in Figure 1. This test and the subsequent analysis show clearly that smart materials can be used to perform closed loop control and suppress the fundamental modes

of the torus. Studies of hardware location based on controllability concepts tied to the newly-developed dynamic model have also been carried out and are currently under review for publication.

**Students Supported:**

Graduates: Brett Williams (MS/PHD), Jake Lewis (MS), Munki Lee (MS), Akhilesh Jha (PHD), Eric Ruggiero (MS/PHD)

Undergraduates: Gil Briand, Matthias Mandin, Marion Sausse, Henry Sodano and Elizabeth Magliula.

**Publications Resulting from this Support:**

***Publications (Journal Articles)***

Jha, A. and Inman, D. J., "Optimal Sizes and Placement of Piezoelectric Actuators and Sensors for an Inflated Torus," submitted to *AIAA Journal of Spacecraft and Rockets*, October 2002.

Jha, A. and Inman, D. J., "Modeling Pressure for Dynamic Analysis of an Inflatable Structure," submitted to *Journal of Sound and Vibration*, September 2002.

Jha, A. and Inman, D. J., "Sliding Mode Control of an Ultra-light Inflatable Structure Using Smart Materials," submitted to *Journal of Vibration and Control*, September 2002.

Park, G., Sausse, M., Inman, D. J., Main, J. A., 2002. "Vibration Testing and Finite Element Analysis of an Inflatable Structure," *AIAA Journal*, to appear.

Park, G., Kim, M., and Inman, D. J., 2002. "Integration of Smart Materials into Dynamics and Control of Inflatable Space Structures," *Journal of Intelligent Material Systems and Structures*, to appear.

Ruggiero, Eric J., Akhilesh Jha, Gyuhae Park, and Daniel J. Inman, 2002. "Gossamer Spacecraft Technology: An Analytical and Experimental Literature Reference Guide," *The Shock and Vibration Digest*, to appear.

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Park, G., Ruggiero, E. and Inman, D. J., "Dynamic Testing of an Inflated Structure using Smart Materials," *Smart Materials and Structures*, 2002, Vol. 11, pp. 147-155.

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Moriera, F.J.O., Arruda, J. R. F., and Inman, D. J., "Design of a Reduced Order H-infinity Controller for Smart Structures Satellite Applications," *Philosophical Transactions of the Royal Society*, Vol. 359, No. 1781, 15 Nov. 2001, pp. 2251-2270.

Williams, R. Brett, Austin, Eric M., and Inman, Daniel J., "Limitations of Using Membrane Theory for Modeling PVDF Patches on Inflatable Structures," *Journal of Intelligent Material Systems and Structures*, Vol. 12, No. 1, January 2001, pp. 11-20.

Kim, M-H., and Inman, D. J., "Spillover reduction in the vibration control of flexible structures using sliding mode observer," *Journal of Vibration and Control*, Vol. 7, No. 7, October, 2001, pp. 1087-1105.

Lewis, J. A. and Inman, D. J., "Finite Element Modeling and Active Control of an Inflated Tours Using Piezoelectric Devices," *Journal of Intelligent Material Systems and Structures*, Vol. 12, No 12, December 2001 (printed in August, 2002), pp. 819-834.

***Publications (Proceedings and Conference Papers):***

Ruggiero, E., Park, G, Inman, D. J. and Wright, J., "Multi-Input, Multi-Output Modal Testing Techniques for a Gossamer Structure," ASME IMECE Adaptive Structures Symposium, New Orleans, LA, November, 2002.

Adachi, K., Park, G. and Inman, D. J., "Passive Damping Augmentation using Macro-Fiber Composite Actuators," Proceedings ASME IMECE Adaptive Structures Symposium, New Orleans, LA, November, 2002.

Ruggiero, Eric J., Gyuhae Park, Daniel J. Inman "Macro-fiber Composite Actuators for Inflatable Structures," *Proceedings of 9<sup>th</sup> International Congress on Sound and Vibration*, July 8-11, 2002, Orlando, FL.

Ruggiero, Eric J., Gyuhae Park, and Daniel J. Inman. "Active Vibration Suppression of Gossamer Spacecraft." *Proceeding of 14<sup>th</sup> U.S. National Congress of Theoretical and Applied Mechanics*, June 23-28, 2002, Blacksburg, VA.

Ruggiero, Eric, Gyuhae Park, Daniel J. Inman, and John A. Main. "Smart Materials in Inflatable Structure Applications," *Proceedings of 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA Gossamer Spacecraft Forum*, April 22-25, 2002, Denver, CO.

Park, G., Sausse, M., Inman, D.J., Main, J.A., 2001. "Smart Materials in Inflatable Structure Applications," *Proceedings of 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA Gossamer Spacecraft Forum*, Denver, CO, 22-25 April 2002.

Jha, A. K. and Inman, D. J., "Piezoelectric actuator and sensor models for an inflated toroidal shell," *SPIE 2002 Smart Materials and Structures Conference*, San Diego, CA, March 17-21, 2002, [paper number 4701-58].

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Jha, A., Kim, M., Leo, D. J. and Inman, D.J., "Sliding Mode Control for the Vibration Suppression of an Inflatable Torus Using Smart Materials", *ASME IMECE Adaptive Structures and Material Systems Symposium*, NY, NY, November 2001, Vol. 3 CD.

Inman, D. J., "Smart Structures: Examples and New Problems", *16th Brazilian Congress of Mechanical Engineering*, Uberlandia, Brazil, November 26-30, 2001, Opening Plenary Lecture, CD ROM Proceedings, pp. 4-14.

Sausse, M., Park, G., Inman, D.J., Main, J.A., "Vibration Testing and Finite Element Analysis of an Inflatable Torus Structure," *Proceedings of 12<sup>th</sup> International Conference on Adaptive Structures and Technologies*, 15-17 October 2001, College Park, MD.



Park, G., Kim, M., Matthias, M., Inman, D.J. "Vibration Testing and Control of Inflatable Space Structures using Smart Materials," *Proceedings of 18<sup>th</sup> ASME Biennial Conference on Mechanical Vibration and Noise*, 9-12 September 2001, Pittsburgh, PA, DETC2001/VIB-21540.

Williams, R. B., Austin, E. M. and Inman, D. J., "Local Effects of PVDF Patches on Inflatable Space-Based Structures," *Proceedings of the 42<sup>nd</sup> AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*, 16<sup>th</sup>-19<sup>th</sup> April 2001, Sheraton Seattle Hotel & Towers, Seattle, WA.

Kim, Myung-Hyun, Park, Gyuhae, and Inman, Daniel J., "Simultaneous Control and Monitoring of Adaptive Structures Using Smart Sensors," *Proceedings of the IMAC-XIX: A Conference & Exposition on Structural Dynamics*, Kissimmee, Florida, 5-8 February 2001.

Inman, D. J. and Hegewald, T., "Simultaneous Health Monitoring and Control of Panels," *Proceedings of the 11<sup>th</sup> International Conference on Adaptive Structures and Technologies*, Nagoya, Japan, 23-26 October 2000, pp. 309-316.

Inman, D. J., Ahmadian, M., and Claus, R. O., "Simultaneous Active Damping and Health Monitoring of Aircraft Panels," *Proceedings of the IUTAM Symposium on Smart Structures and Structronic Systems*, Kluwer Academic Publishers, Netherlands Magdeburg, Germany, 26-29 September 2000, pp. 1-9.

Kim, Myung-Hyun, and Inman, Daniel J., "Spillover Reduction in the Vibration-control of Flexible Structures Using Sliding Mode Observer," *Proceedings of the Eighth Conference on Nonlinear Vibration, Stability, and Dynamics of Structures*, Blacksburg, Virginia, 23-27 July 2000.

Inman, Daniel J., and Hegewald, Thomas, "Suppressing Plate Vibrations with Smart Materials" *Proceedings of the Seventh International Congress on Sound and Vibration*, Garmisch-Partenkirchen Congress Center, Germany, 4-7 July 2000.

Briand, G., Wicks, A. L., and Inman, D. J., "Vibration Testing for Control of Inflated Objects" *Proceedings of the SECTAM-XX*, Callaway Gardens, Pine Mountain, Georgia, 16-18 April 2000, pp. 57-62.

Agnes, G. S., Inman, D. J., Rogers, J. R., Williams, R. B., and Briand, G., "Smart Structures and Inflatable Satellite Components," *Proceedings of the Tenth International Conference on Adaptive Structures and Technologies*, Paris, France, 11-13 October 1999, pp. 157-162.

Inman, D. J. and Agnes, G. S., "Smart Structures for Vibration Suppression of Optical Surfaces," *Proceedings of the AFOSR Structural Mechanics Workshop*, Wright Patterson AFB, Ohio, 27-29 September 1999, pp. 69-74.

### ***Keynotes, Plenary Addresses and Award Lectures:***

Inman, D. J., "Ultra Flexible Spacecraft and Morphing UAVs", ICAM Workshop on Control and Identification in Honor of Gene Cliff's Retirement, September 27-28, 2002, Blacksburg, VA.

Inman, D. J., "Applications of Smart Materials in Structures" Tutorial, National Space and Missiles Materials Symposium, June 24-28, 2002, Colorado Springs, CO.

Inman, D. J., "Historical Perspective for Gossamer Structures: Lessons Learned from the Large Flexible Space Structure Era", AFRL/DARPA Workshop on Ultra-Large Space Antenna Structures, May 21-22, 2002, Santa Fe, New Mexico.

Inman, D. J., "Smart Structures in Space", 21st Southeastern Conference on Theoretical and Applied Mechanics, Keynote Address, May 19-21, 2002, Orlando, Florida

Inman, D. J., "Modeling Passive and Active Damping," International Workshop on Passive and Active Damping- Directions for the Next Decade, Keynote address, June 18-20, 2001, Neu-Ulm, Germany <http://www.ae.go.dlr.de/damping/start.html>

Inman, D. J., "Application of Smart Structures for Suppression Vibration," *International Scientific Conference-Mechanical Engineering 2000*, Bratislava, Slovak Republic, 15 November 2000 (Plenary Address).

Inman, D. J., "Smart Structures: Past, Present, and Future," *International Symposium on Smart Structures and Microsystems 2000*, Hong Kong, 19-21 October 2000 (Keynote Address).

Inman, D. J., "Smart Structures - Where's the Beef?" ASME Adaptive Structures and Material Systems Prize Lecture, presented at the 41<sup>st</sup> AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Atlanta, Georgia, 3-6 April 2000.

### ***Other Lectures***

Ruggiero, Eric J. "Vibration Testing and Analysis of Inflatable Structures Using Smart Materials." *Naval Research Laboratory Presentation, Multifunctional Materials Branch*, March 7, 2002, Washington, D.C.

Inman, D. J., "Multifunctional Structures for the Next Millennium," Panel Discussion on the Future of Structural Dynamics" -41<sup>st</sup> AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Atlanta, Georgia, 3-6 April 2000.

Inman, D. J., "Smart Structures for Vibration Suppression of Optical Surfaces," *Proceedings of the Air Force Office of Scientific Research Structural Mechanics Workshop*, Wright Patterson Air Force Base, 27-29 September 1999, pp. 69-74.

(Also presented lectures by the same title at the AFOSR Structural Mechanics review in Columbus Ohio, October, 2000; the review in Washington, DC in October 2001; and again at the review in Roslyn, VA in September, 2002.)